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Design, loading, and water quality in recirculating systems for Atlantic Salmon (*Salmo salar*) at the USDA ARS National Cold Water Marine Aquaculture Center (Franklin, Maine)

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ABSTRACT

The Northeastern U.S. has the ideal location and unique opportunity to be a leader in cold water marine finfish aquaculture. However, problems and regulations on environmental issues, mandatory stocking of 100% native North American salmon, and disease have impacted economic viability of the U.S. salmon industry. In response to these problems, the USDA ARS developed the National Cold Water Marine Aquaculture Center (NCWMAC) in Franklin, Maine. The NCWMAC is adjacent to the University of Maine Center for Cooperative Aquaculture Research on the shore of Taunton Bay and shares essential infrastructure to maximize efficiency. Facilities are used to conduct research on Atlantic salmon and other cold water marine finfish species. The initial research focus for the Franklin location is to develop a comprehensive Atlantic salmon breeding program from native North American fish stocks leading to the development and release of genetically improved salmon to commercial producers. The Franklin location has unique ground water resources to supply freshwater, brackish water, salt water or filtered seawater to fish culture tanks. Research facilities include office space, primary and secondary hygiene rooms, and research tank bays for culturing 200+ Atlantic salmon families with incubation, parr, smolt, on-grow, and broodstock tanks. Tank sizes are 0.14 m^3 for parr, 9 m^3 for smolts, and 36, 46 and 90 m^3 for subadults and broodfish. Culture tanks are equipped with recirculating systems utilizing biological (fluidized sand) filtration, carbon dioxide stripping, supplemental oxygenation and ozonation, and ultraviolet sterilization. Water from the research facility discharges into a wastewater treatment building and passes through micro-screen drum filtration, an inclined traveling belt screen to exclude all eggs or fish from the discharge, and UV irradiation to disinfect the water. The facility was completed in June 2007, and all water used in the facility has been from groundwater sources. Mean facility discharge has been approximately 0.50 m^3/min (130 gpm). The facility was designed for stocking densities of 20–47 kg/m^3 and a maximum biomass of 26,000 kg. The maximum system density obtained from June 2007 through January 2008 has approached 40 kg/m^3, maximum facility biomass was 11,021 kg, water exchange rates have typically been 2–3% of the recirculating system flow rate, and tank temperatures have ranged from a high of 15.4 °C in July to a low of 6.6 °C in January 2008 without supplemental heating or cooling.

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1. Introduction

The National Cold Water Marine Aquaculture Center (NCWMAC) is a new research facility established by the USDA ARS to improve the efficiency and sustainability of cold water marine finfish farming. The initial focus of center research in Franklin (i.e., the basis for this facility's design) is to develop an Atlantic salmon breeding program that will improve fish growth and other economically important traits in stocks that are entirely composed of North American germplasm. Research objectives are to utilize a family-based selective breeding program to developed improved North American Atlantic salmon lines for U.S. producers and consumers. Production modeling and bioplan for the Franklin facility were completed in 2004 and the final design of the aquaculture systems was completed in 2005. Construction began in Franklin in May 2006 and was completed by May 2007.

1.1. Design constraints

The facility was designed to meet strict biosecurity standards for raising Atlantic salmon from eggs to 4-year-old fish while maintaining separate fish culture systems for separate year classes,

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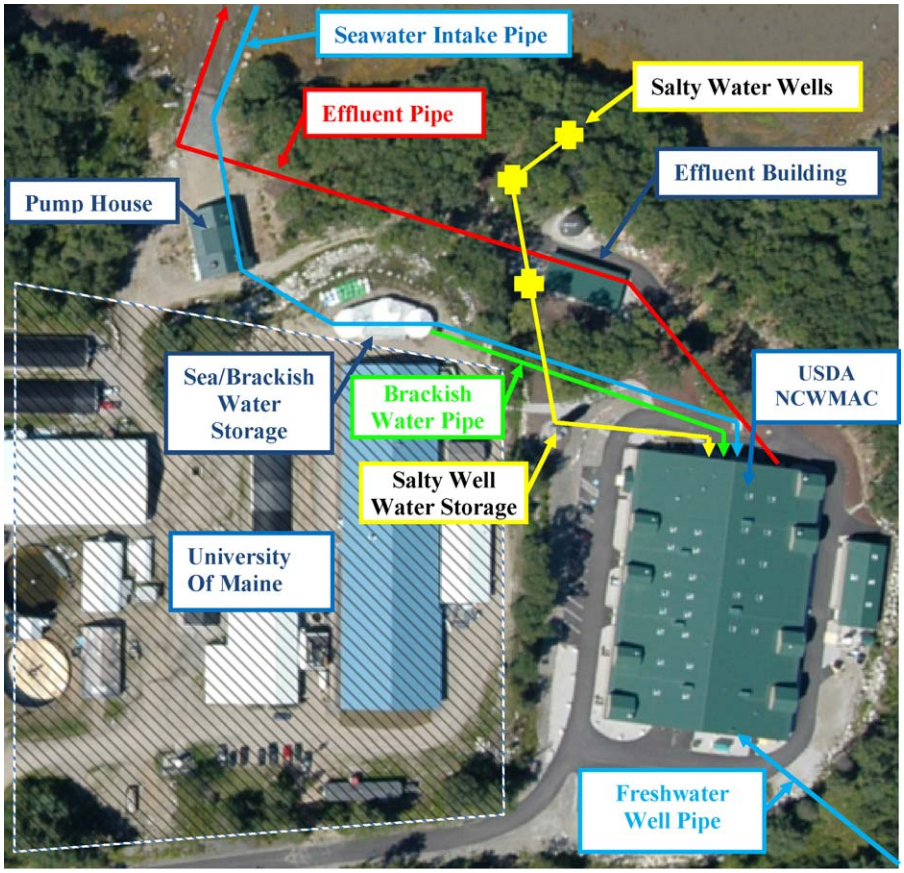


Fig. 1. Aerial view of the USDA ARS National Cold Water Marine Aquaculture Center in Franklin, Maine. The center is adjacent to the University of Maine's Center for Cooperative Aquaculture Research and is supplied with water from freshwater, brackish water (1–2 ppt), salty well water (~15 ppt), and seawater.

plus provide additional small-scale research tank bay space for flexible use. The Franklin research site had a disinfected and filtered surface seawater intake from Taunton Bay, but only limited well water supplies, which would force selection of water recirculation technologies for fish production when anything less than full-strength seawater was required (Fig. 1). However, different wells on-site provided a range of salinities, which, when used with chilled recirculating systems, could be used to meet the bioplan requirement for production systems with varying salinities (i.e., 0–35 ppt) and temperatures (i.e., 4–15 °C). The recirculating systems had to be extremely reliable, compact, and relatively simple to operate, and also maintain exceptional water quality that would be required to produce a healthy 4-year-old salmon broodstock. The facility also has a 650 kW on-site diesel generator to provide electrical power during commercial power interruptions. In addition, all effluent had to be filtered, disinfected, and provided with fish exclusion before discharge to Taunton Bay. Total project budget for the main research building, two separate research tank buildings for isolation research, the effluent building, well water supply lines, and the discharge pipe was approximately $13 million for design and construction.

1.2. Aquaculture system designs

The principal USDA research building is approximately 3700 m^2 (40,000 ft^2) and includes offices, two analytical laboratories, primary and secondary hygiene rooms, two research tank bays, and eight separate fish culture systems for egg incubation, parr culture, smolt culture, 2nd year on-grow, and 3- and 4-year-old broodstock culture (Tables 1 and 2, plus Fig. 2). The facility can culture 224 salmon families in 0.1-m^3 parr tanks, six 9-m^3 smolt tanks, four 36-m^3 (2nd year) on-grow tanks, eight 46-m^3 (3rd year)

Table 1
Description of fish culture systems, i.e., number of tanks, tank volumes, area of culture tank room, and area of associated water treatment room that are used for culturing Atlantic salmon in the breeding program at the USDA ARS National Cold Water Marine Aquaculture Center in Franklin, Maine.

Culture system	Tanks (#)	Indiv. tank size (m^3)	Total tank volume (m^3)	Pump sump (m^3)	Biofilter/LHO volume (m^3)	Culture tank room area[a] (m^2)	Associated water treatment room area (m^2)
Parr	234	0.14	33	9.0	13.2	290	64
Smolt 1	3	9	27	7.2	13.7	78	70
Smolt 2	3	9	27	7.2	13.7	78	66
On-grow	4	36	144	22.6	42.7	310	98
3 years broodstock 1	4	46	184	22.6	42.7	310	100
3 years broodstock 2	4	46	184	22.6	42.7	310	120
4 years broodstock	1	90	90	13.3	32.2	190	100
Total	253		689	104.5	201.1	1560	620

[a] Excluding adjacent areas that are used for fish feed storage, general storage, waste removal, laboratory work, and hygiene.

Table 2
Description of the design recycle flow rates, makeup flow rates, design feeding rates, predicted maximum biomass, and maximum cumulative feed burden in all systems used for culturing Atlantic salmon in the breeding program at the USDA ARS National Cold Water Marine Aquaculture Center in Franklin, Maine.

Culture system	Predicted maximum biomass (kg/m^3)	Design recirculation flow rate (l/min)	Makeup water required at 2.5% of flow (l/min)	Predicted maximum feeding rate (kg/day)	Cumulative feed burden[c] (mg/l)
Parr	1320	1,250	31	17	380
Smolt 1	1100	870	22	45	1420
Smolt 2	1100	870	22	45	1420
On-grow	5760	4,470[a]	112	101	626
3 years broodstock 1	7360	4,470[a]	112	165	1020
3 years broodstock 2	7360	4,470[a]	112	165	1020
4 years broodstock	3600	2,230	56	26	320
Total	NA[b]	18,630	467	NA[b]	NA[b]

[a] Actual flow during this period was restricted to approximately 50% of the design flow (to conserve energy), because some tanks in each system were not fully loaded. However, all systems are operated at their design flow when the culture tanks are all fully loaded.
[b] All systems do not achieve maximum feeding rate or maximum biomass at the same time, so totalizing each maximum is not relevant.
[c] Daily maximum expected feeding rate divided by makeup water flow rate.

and one 90-m^3 (4th year) broodfish tanks. Fish culture tanks used in the salmon breeding program are equipped with recirculating systems that range in size from 780 to 4470 l/min (Figs. 3–5). Criteria used to design the water treatment components and culture tanks in each recycle systems are presented in Tables 2 and 3. These recycle systems typically utilize dual-drain culture tanks (except in the parr system) and radial flow settlers to treat the bottom-center drain exiting each culture tank (except in the parr system) and then a centralized system containing micro-screen filtration, biological (fluidized sand) filtration, carbon dioxide stripping, supplemental low head oxygenation, ozonation, and ultraviolet sterilization (only in the parr and smolt systems) to treat the entire recirculating flow before it is returned to the culture tanks (Figs. 3–5). A process flow drawing for one of 3rd year broodstock systems is provided (Fig. 5); it is representative of the process flow paths used in the other systems. Dual-drain circular

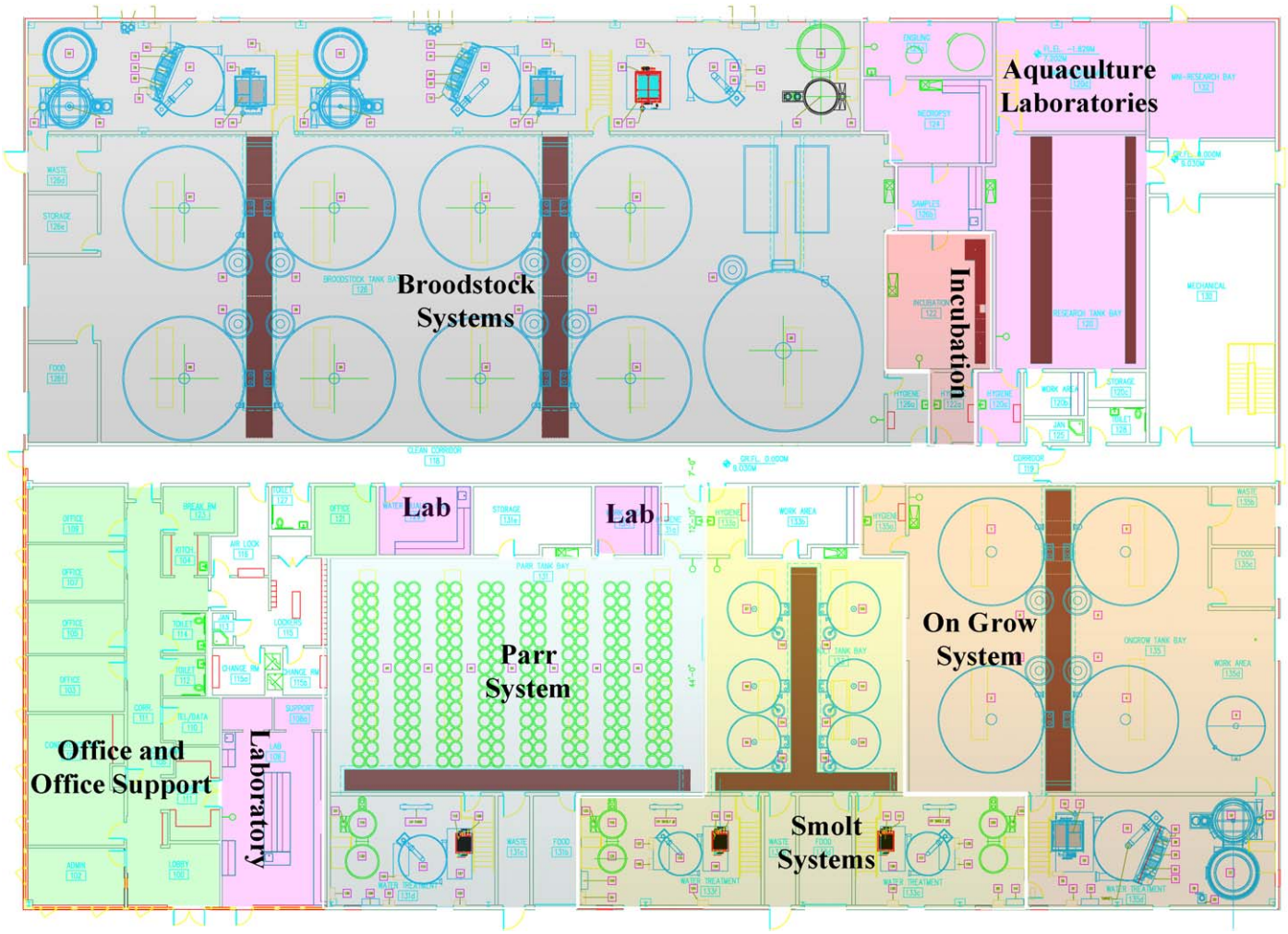


Fig. 2. Plan view drawing of the principal USDA research building includes shows offices, two analytical laboratories, primary and secondary hygiene rooms, two research tank bays, and eight separate fish culture systems for egg incubation, parr culture, smolt culture, 2nd year on-grow, and 3- and 4-year-old broodstock culture.

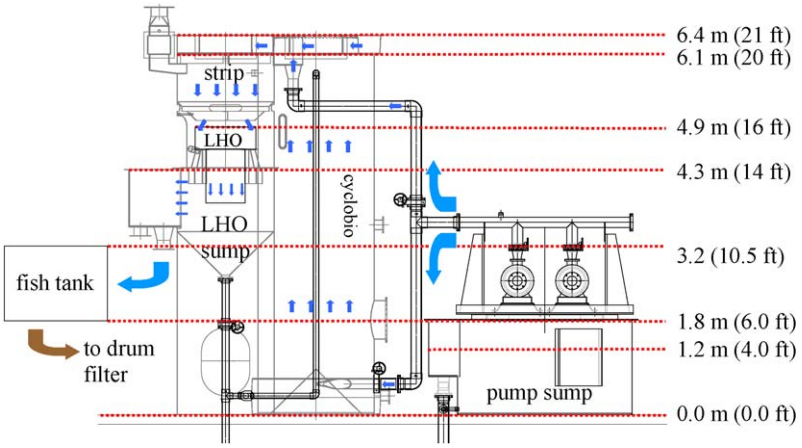


Fig. 3. Diagrammatic representation of water flow and water treatment components (excluding drum filter and radial flow settlers) of a typical recirculating filtration system used at the USDA ARS National Cold Water Marine Aquaculture Center in Franklin, Maine.

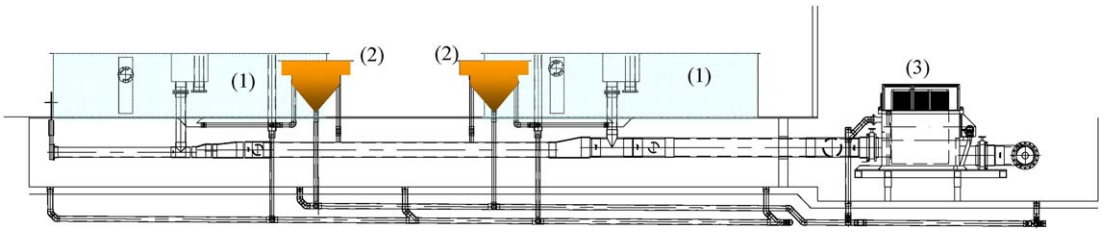


Fig. 4. Diagrammatic representation of the dual-drain circular culture tanks in a typical recirculating filtration system used at the USDA ARS National Cold Water Marine Aquaculture Center in Franklin, Maine; water exiting the bottom-center drain of the culture tank (1) is first treated across a radial flow settler (2) before the flow is piped, along with the flow exiting the tank sidewall drain, to the micro-screen drum filter (3).

tanks were flushed at a mean hydraulic exchange rate of 26 min (parr tanks) to 41 min (3- and 4-year-old broodstock tanks) and a bottom center drain flow of 6–10 l/min per m^2 plan area (Davidson and Summerfelt, 2004). Flow injection manifolds were built into the culture tank walls to allow staff to adjust water rotational velocities by capping or uncapping nozzle inlets. Radial flow settlers treating the water exiting the bottom-center drain (Fig. 4) were sized at a surface loading rate of approximately 0.0031 m^3/s of flow per square meter of settling area (4.6 gpm/ft^2; Davidson and Summerfelt, 2005). The cone base of each settler (Fig. 4) was manually flushed once daily (to the solids thickening belt filter in the effluent treatment building) and no flow was discharged from the bottom of the cone during normal operation. Cyclobio™ fluidized sand biofilters (Fig. 3; Summerfelt, 2006) were sized to treat from 50% to 80% of the total recirculating flow using relatively fine silica filter sand (0.18 mm effective size) that expanded 60–100% (before biofilm establishes) at a superficial velocity of 0.76 cm/s. All of the recirculating flow passed through forced-ventilated cascade aeration columns (Fig. 3) contained 0.6 m depth of 5 cm diameter random plastic packing and were hydraulically loaded at approximately 0.02 m^3/s per m^2 plan area (30 gpm/ft^2) with an air:water loading of at least 10:1 (Summerfelt et al., 2000). The stripping columns were stacked above low head oxygenation units (Fig. 3) that were hydraulically loaded at approximately

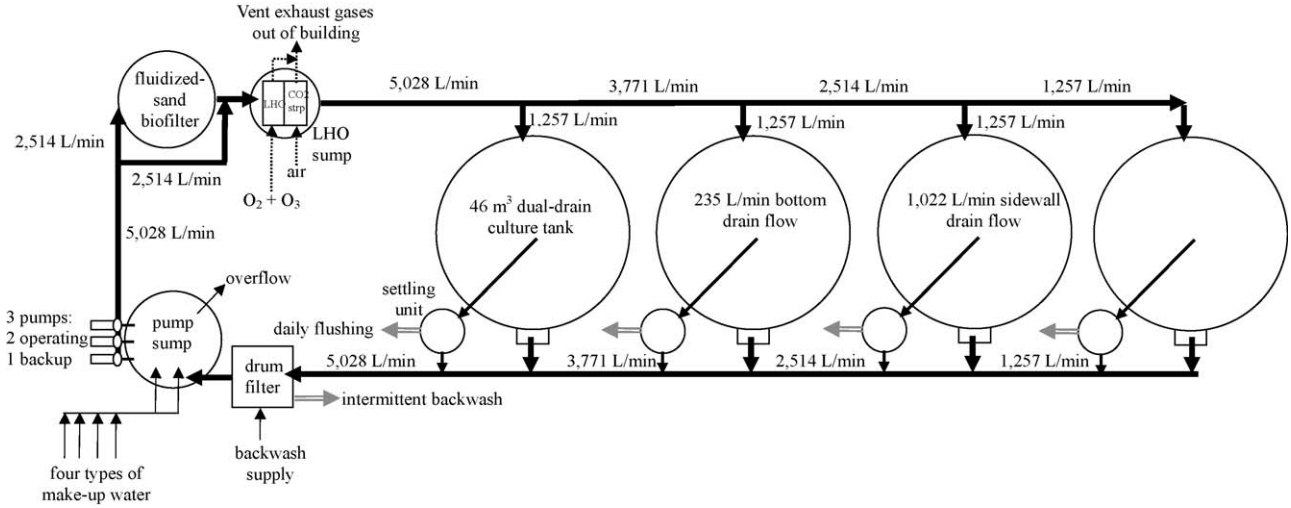


Fig. 5. Process flow drawing of one of the 3rd year broodstock systems at the USDA ARS National Cold Water Marine Aquaculture Center in Franklin, Maine.

Table 3
Criteria used to design the water treatment components and culture tanks in each recycle systems.

Parameter or criteria	Value
Culture tanks	
Max. culture tank inlet oxygen conc.	16 mg/l (parr, on-grow, brood) to 19 mg/l (smolt)
Mean culture tank outlet oxygen conc.	10 mg/l
Culture tank exchange rate	25 min (parr, smolt) to 40 min (on-grow, brood)
Critical features	All fiberglass construction; dual-drain design (all but parr tanks); flow inlet manifold integrated into tank wall
Radial flow settlers	
Size of sieve panel openings	0.0031 m^3/s per m^2 plan area (4.6 gpm/ft^2)
Angle between sediment cone and skirt	45°
Critical features	All fiberglass construction; cylinder at tank center dampens turbulence and directs inlet flow; v-notch collection launder about top perimeter
Drum filters	
Size of sieve panel openings	60 μm
Critical features	Inlet and outlet overflow weirs; automatic backwash on according to drum filter water level; all stainless or plastic construction
Fluidized-sand biofilters	
Sand size (mean equivalent diameter)	0.18 mm
Uniformity coefficient of sand	≤1.7
Superficial velocity (hydraulic loading)	0.76 cm/s; clean sand expansion 50–100%
Initial unexpanded sand depth	2.0 m (after fines have been flushed)
Critical features	CycloBio units; all fiberglass construction; v-notch collection launder about top perimeter
Cascade aeration/stripping columns	
Packing type	5-cm diameter plastic random packing
Packing depth	0.8 m
Volumetric gas to liquid ratio (G:L)	≥10:1
Hydraulic loading rate	0.02 m^3/s per m^2 plan area (30 gpm/ft^2)
Critical features	All fiberglass and plastic construction; forced ventilated; nozzle plate distributes flow; water enters via channel from biofilter and sidebox port from pumps; water exits down onto deflector plate above LHO; demisting chamber at air outlet
Low head oxygenation units	
Water level above orifice plate	20 cm
Cascade height	46 cm (elevation between orifice plate and water level below)
Submergence depth	76 cm (elevation between water level and bottom of LHO)
Hydraulic loading rate	0.034 m^3/s per m^2 plan area (50 gpm/ft^2)
Critical features	All fiberglass construction (ozone resistant resin); deflector plate between LHO and stripper directs inlet water to perimeter of LHO orifice plate
Ozonation	
Dosing rate	0.015–0.025 kg ozone per 1 kg feed fed
Critical features	O_3 generated in pure O_2 feed gas before gas is transferred at each LHO; ozone dose controlled via ORP
UV irradiation units (tube and shell)	
UV dose	50 mW s/cm^2 @ end of lamp life and 90% UVT
Critical features	Designed for low headloss; only installed in parr and smolt systems

0.034 m^3/s per m^2 plan area (50 gpm/ft^2; Summerfelt, 2003). Ozone was generated in the oxygen feed gas before it was supplied to each low head oxygenator (Summerfelt, 2003) and dose was controlled manually and sometimes using oxidative reduction potential (set-point of 350 mV) measured just before water returns to the culture tank (Summerfelt et al., 2009). Ozone dose is supplied at approximately 15–25 g per kilogram feed. Approximately 1 m of head was used to return the water from the sump beneath the low head oxygenation unit, through UV irradiation units (in the parr and smolt systems, but not in the larger recycle systems), and back to the culture tanks (Fig. 3). UV irradiation units were sized to treat the required flow rate for each system at a dosage level of 50,000 μW s/cm^2at the end of lamp life), assuming 90% transmittance of UV through a 1-cm long path of water. Excess water flow in the low head oxygenation unit's sump was by-passed back to the pump sump, through the drum filter. Most systems also include chilling units to individually adjust water temperature to meet biological requirements. Recirculating systems have water quality instrumentation to monitor and alarm temperature, oxygen, and oxidation–reduction potential (ORP/ozone) levels. Temperature and oxygen levels are provided to a computerized feed control system that dispenses feed from robots traveling on rails above culture tanks or individual tank feeders.

Four different water sources are supplied to the fish culture systems and two research tank bays to provide the most flexibility meeting the requirements of the bioplan and a dynamic research program. Water can be supplied to fish culture tanks from filtered and UV treated seawater from adjacent Taunton Bay, fresh well water (0 ppt), low salinity brackish well water (~2 ppt), and higher salinity brackish well water (12–14 ppt). Typical ground water temperature is a constant 8–9 °C. However, before entering the fish culture facilities, the higher salinity brackish well water is treated across a cooling tower (located above a small reservoir tank) to evaporative cool this water supply when dew point temperatures are especially low in late fall, all winter, and early spring and also warm the well water during the summer. Makeup water to each system is typically about 2.5% of the recirculation flow rate and is monitored using a turbine flow meter connected to the computer controlling the feeding system.

Overflow water from all of the fish culture systems is collected and piped through an effluent treatment building where it is treated using micro-screen drum filtration to remove particulates, inclined traveling belt filtration to exclude all eggs or fish, and UV irradiation to disinfect the water before it is discharged to adjacent Taunton Bay (Figs. 6 and 7). In a parallel treatment path, biosolids contained in the facility's micro-screen drum filters and particle

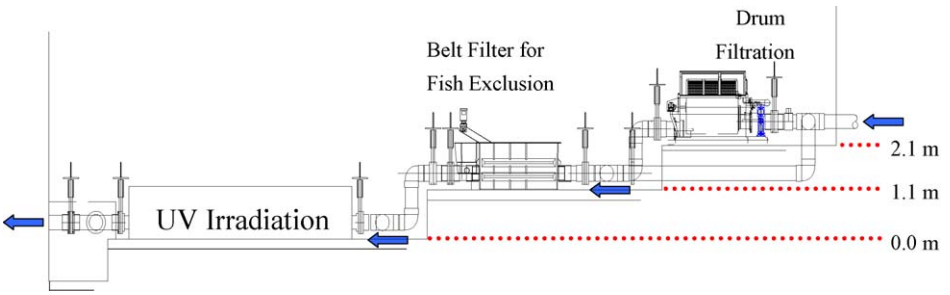


Fig. 6. Diagram (profile view) of the effluent treatment building processes used to treat all water overflowing or flushed from the fish culture systems; water is treated using micro-screen drum filtration to remove particulates, inclined traveling belt filtration to exclude all eggs or fish, and UV irradiation to disinfect the water before it is discharged to adjacent Taunton Bay.

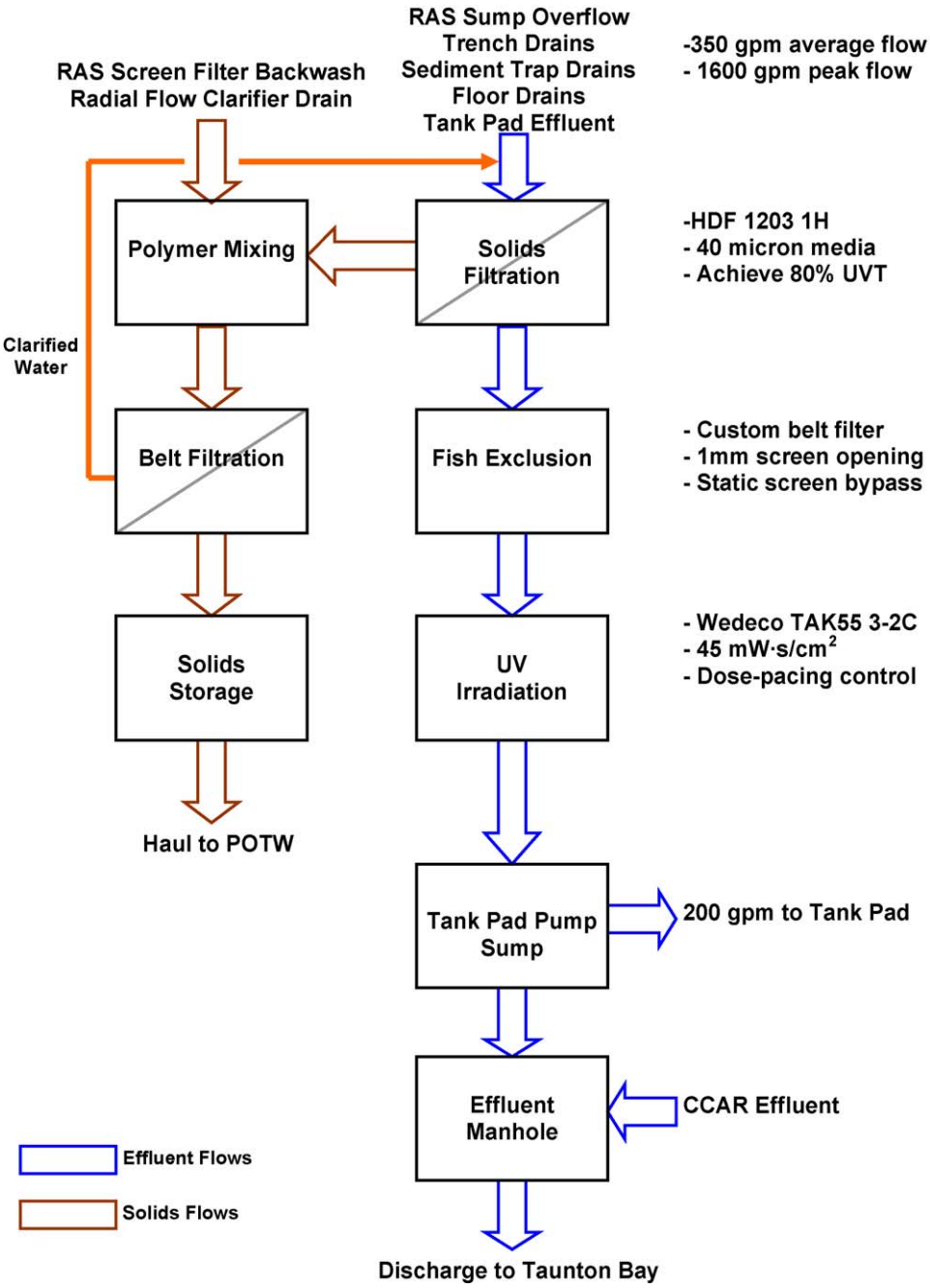


Fig. 7. Process flow drawing of the effluent treatment processes used at the USDA ARS National Cold Water Marine Aquaculture Center in Franklin, Maine.

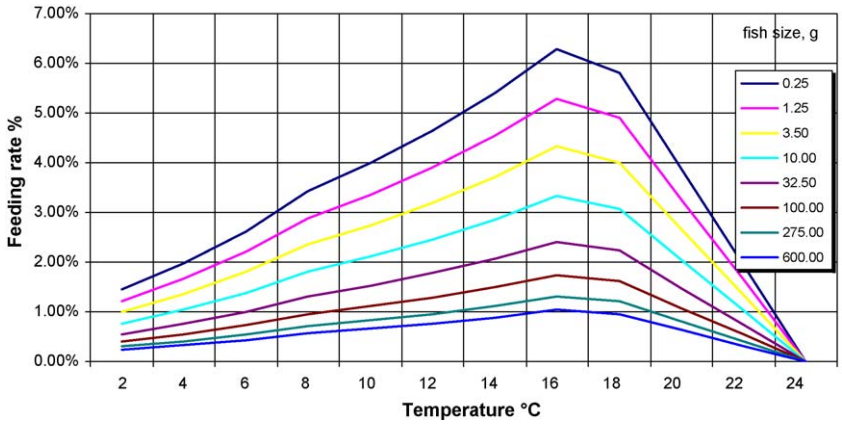


Fig. 8. Feeding rates used at the USDA ARS National Cold Water Marine Aquaculture Center in Franklin, Maine based on fish size and water temperatures.

trap backwash are captured and thickened across an inclined belt filter, after which the biosolids are held in a slurry storage tank until disposal (Fig. 7).

2. Methods

2.1. Fish culture

Stocking and culture of Atlantic salmon in the different fish culture systems is based on life stage and separation of year classes. The incubation system is for eggs and fry before first feeding (October–February), the parr system is for first feeding fry to 30–40 g salmon (March–December), the smolt system is for 30–40 to 100 g salmon (January–May), the on-grow system is for 100 g to 1.0 kg salmon in their 2nd year (May–May), the 3-year-old broodstock system is for 1.0–3.0 kg salmon (June–May), and the 4-year-old broodstock system is for growing salmon to 3.0–6.0 kg from June until October when they will be spawned.

Up to 224 families of Atlantic salmon with 300–500 eggs/family are held in the incubation system. Approximately 150–250 fish per family have been raised through parr size. Typically 30–40 smolts per family are maintained in smolt tanks and on-grown through their 2nd year of age (reaching approximately 1.0 kg/fish). Additional smolts are cultured for stocking into industry collaborator net pens for performance evaluations and additional research studies. These 30–40 fish per family are reared to the end of their 3rd year and a size of approximately 3.0 kg (possibly smaller). Selection of 4-year-old fish for spawning is based on calculation of estimated breeding values from net pen performance evaluations. Breeding values are an estimate of the ability of an individual to produce superior offspring and are based on measurements of performance, using phenotypic values, taken on the animal itself or its relatives (the fish stocked into net pens). Although additional traits of economic importance should and will be considered in the future, growth or carcass weight are considered to be of primary importance and are traits with major impact on economic return. Selection or culling of broodfish occurs when fish are moved from 3-year-old broodstock tanks into the 4-year broodstock system prior to the spawning season.

Final stocking density, depending upon life-stage, limits the total biomass that can be supported in each salmon rearing system. Using an expected biomass of 40 kg/m^3 of tank volume as the maximum biomass in each fish culture system, approximately 1600 kg of parr, 2200 kg smolt, 5760 kg of 2nd year broodstock, 14,720 kg of 3rd year broodstock, and 3600 kg of 4th year broodstock can be maintained in the breeding program fish culture systems. Production systems are stocked below maximum biomass and do not reach their maximum biomass at exactly the same time. Fish are fed a commercially available Atlantic salmon diet in multiple daily feedings using computer software at a rate determined by fish size and temperature (Fig. 8). The computer programs were developed from experimental growth models validated from commercial data for various environmental conditions and different genetic stocks (Ursin, 1967; From and Rasmussen, 1984; Ruohonen and Makinen, 1992: Seppo Tossavainen, Arvotec, personal communication).

2.2. Water quality analyses

Total ammonia, nitrite, nitrate nitrogen, pH, CO_2, and alkalinity in the fish culture systems were measured weekly from water

Table 4
Actual fish numbers, stocking weight, final weight, maximum biomass, maximum density, maximum daily feeding rates, cumulative feed burden, makeup water flow loading, and recirculating water flow loading for each of the systems used to culture Atlantic salmon at the USDA ARS National Cold Water Marine Aquaculture Center in Franklin, Maine from June 2007 through January 2008.

System	Fish/age	Fish (n)	Stocking weight (g)	Final weight (g)	Maximum biomass (kg)	Maximum density[a] (kg/m^3)	Max. feed (kg/day)	Cumulative feed burden[b] (mg/l)	Makeup flow loading[c] (l/min per kg fish)	Recirc flow loading[d] (l/min per kg fish)
Parr	YC2006 <1 year	18,400	0.1	40	736	39.0	9.2	177	0.049	1.7
Smolt 1	YC2006 1 year+	7,421	45	120	891	32.9	8.9	213	0.033	0.98
Smolt 2	YC2006 1 year+	4,772	45	120	573	21.2	5.7	136	0.051	1.5
On-grow	YC2005 2 years	2,683	185	1310	3515	32.5	12.2	90	0.027	0.64
3 years broodstock 1	YC2004 3 years	2,006	816	2179	4361	23.7	18.0	108	0.027	0.51
3 years broodstock 2	YC2003 4 years	493	2600	4941	2436	17.7	9.0	54	0.048	0.92
4 years broodstock	YC2003 4 years	270	3500	4931	1332	14.8	4.1	49	0.044	1.7

[a] Density calculated from actual number of tanks stocked with fish.
[b] Daily feed rate divided by makeup water flow rate.
[c] Makeup water flow per unit biomass carried in each system.
[d] Recirculating water flow per unit biomass carried in each system.

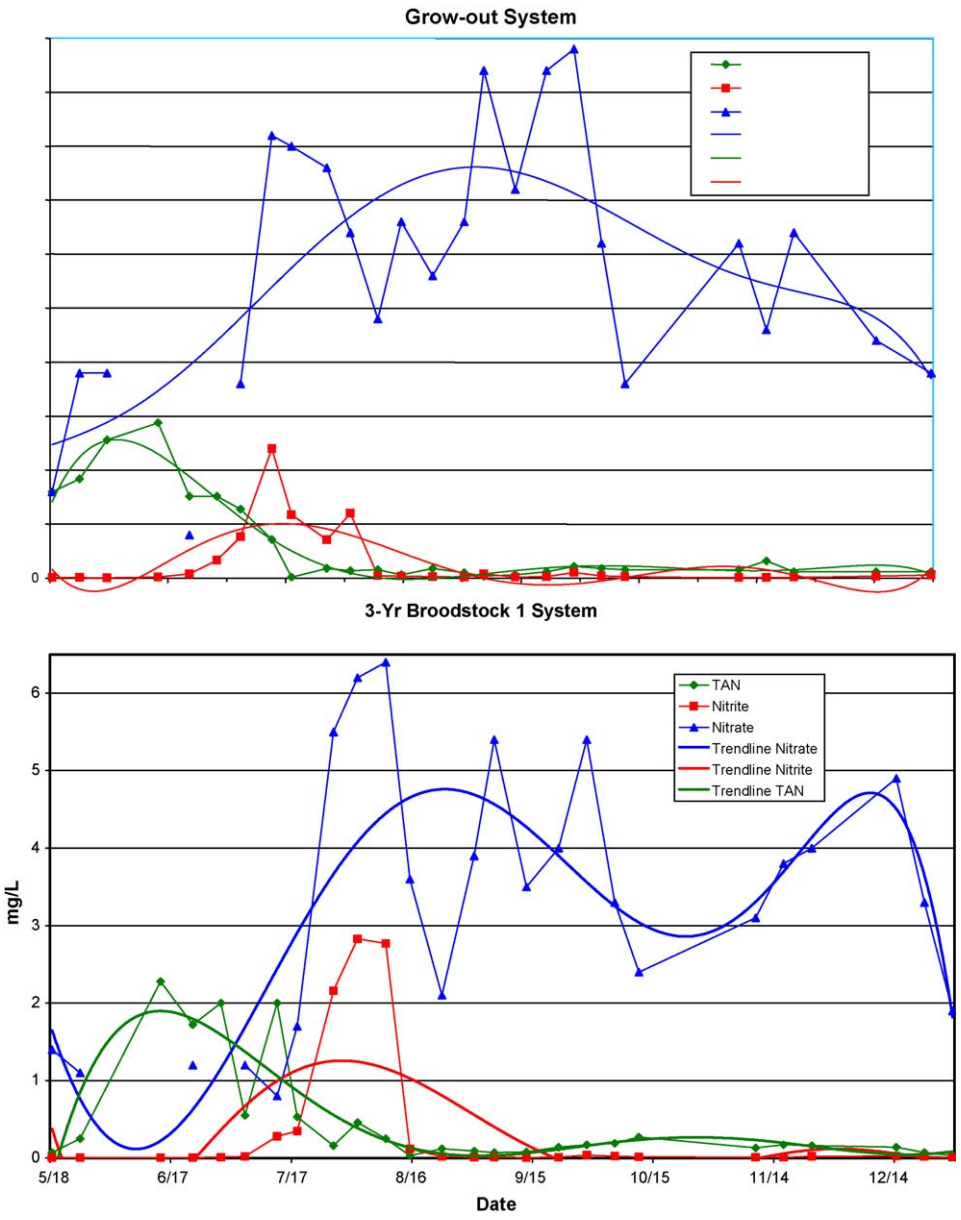


Fig. 9. Changes in total ammonia-, nitrite-, and nitrate-nitrogen in grow-out and 3-year broodstock 1 systems from May through December 2007.

samples taken from pump sumps. Dissolved oxygen, temperature, salinity, and ORP were measured continuously with calibrated probes (Point Four Systems, Coquitlam, BC, Canada). Total ammonia, nitrite, nitrate nitrogen, alkalinity, and CO_2 were measured using chemical reagents (Hach Chemical, Loveland, CO) and Hach DR850 spectrophotometer and pH meters.

3. Results and performance

3.1. Recycle system loading and water quality

Actual fish numbers, stocking weight, final weight, maximum biomass, maximum density, maximum daily feeding rates,

Table 5
Minimum, maximum, and mean total ammonia-nitrogen (TAN), nitrite-nitrogen, nitrate, salinity, carbon dioxide (CO_2), and makeup water flows in parr, on-grow, and 3-year broodfish 1 recirculating fish culture systems at the USDA ARS National Cold Water Marine Aquaculture Center in Franklin, Maine from May 2007 through December 2007.

System	TAN (mg/l)			Nitrite (mg/l)			Nitrate (mg/l)			Salinity (ppt)			CO_2 (mg/l)			Makeup flow (l/min)		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Parr	0.03	0.6	0.166	0.003	1.02	0.15	0.7	11.5	2.81	0.3	3.4	1.7	0.1	5.2	2.0	17	44	36
Smolt 1	0.04	0.16	0.08	0.003	0.01	0.01	0.5	3.0	1.69	2.3	2.8	2.5	0.9	8.0	3.8	35	31	29
Smolt 2	0.0	0.19	0.09	0.004	0.16	0.02	0.7	5.5	2.33	2.3	2.9	2.5	0.9	6.0	3.9	17	31	29
On-grow	0.01	1.44	0.315	0.005	1.20	0.14	0.4	4.9	2.88	4.9	18	13.7	4.3	13.9[a]	8.6	70	123	94
Brood #1	0.03	2.28	0.467	0.003	2.83	0.34	0.8	6.4	3.34	0.2	18.2	13.2	0	9.7[a]	4.7	68	156	116

[a] The dissolved CO_2 was higher in the on-grow and 3-year-old broodstock systems during this period because flow had been restricted to approximately 50% of the design flow to conserve energy, i.e., only one of the two recirculating pumps in each system was operated.

cumulative feed burden, makeup water flow loading, and recirculating water flow loading for each of the systems are reported in Table 4.

Fish were moved into the new systems before nitrification could be established in the biological filters due to tank space limitations in temporary rearing facilities. Concentrations of total ammonia-, nitrite-, and nitrate-nitrogen followed typical startup patterns for fish stocked into new recirculating fish culture systems (Timmons et al., 2002). Total ammonia nitrogen typically increased and peaked during the first month after stocking, nitrite nitrogen increased and peaked generally within 2 months, and nitrate increased and stayed relatively constant within 3 months (Fig. 9). During biofilter startup, technicians used makeup water flows to manage maximum concentrations of toxic nitrogen compounds.

The water quality maintained within each recirculating system during the 1st year of operation was used as a metric to judge system performance. Mean water quality parameters (Table 5 and Figs. 9 and 10) were within the range of acceptable levels for salmonid culture (Piper et al., 1982). In fact, mean total ammonia nitrogen (<0.5 mg/l) concentrations were comparable or less than what is encountered in flow-through systems. Feeding rates (Table 4) were highest in the 3-year broodstock system, where mean total ammonia and nitrite nitrogen concentrations were 0.315 and 0.14 mg/l, respectively (Table 5). These results were expected, as fine sand fluidized-sand biofilters used in salmonid systems are known to maintain high total ammonia nitrogen removal efficiencies and low nitrite nitrogen concentrations (Summerfelt, 2006). In addition, the feed loading on these water recirculating systems used for broodstock development was relatively low (0.1–0.2 kg feed per m^3 makeup water) compared to more heavily stocked and fed grow-out systems that can achieve 0.53 and 5.3 kg/m^3 makeup water flow for high and low makeup conditions (Davidson et al., in press). When mean daily water temperatures had dropped to approximately 8 °C in December of 2007 (Fig. 10), these biofilters continued to maintain total ammonia nitrogen and nitrite nitrogen concentrations of approximately ≤0.1–0.2 mg/l. Similar inorganic nitrogen concentrations (Fig. 11) and water temperatures (not shown) were measured during November and December 2008 and January 2009. Similar patterns were measured in parr and on-grow fish culture systems, but at lower concentrations (not shown). Although makeup water supplied to the fish culture systems was approximately 2.5% of the recirculating flow rate and the well water temperatures were 8–9 °C, ambient air temperatures in the fish culture rooms impacted tank temperatures. Water temperature and dissolved oxygen levels fluctuated diurnally and seasonally (Fig. 10). Water temperatures were highest in July and August where they peaked at 13.8 °C and lowest in December at 5.5 °C (Fig. 10). Dissolved oxygen levels were more stable and were generally maintained above 8 ppm in the culture tanks.

Salinities in the fish culture system were stable and had limited variation (Table 5) because makeup water came from groundwater sources. The parr and smolt culture systems were supplied with either freshwater or brackish water (range 0.3–3.4 ppt) while the on-grow and broodstock systems were supplied with higher salinity brackish water (0.3–18.2 ppt) except during the spawning season when 4-year-old spawning broodfish were supplied with freshwater.

Carbon dioxide varied with fish biomass in the different fish culture systems and ranged from 0 to a maximum of 13.9 mg/l in the on-grow system (Table 5). Average CO_2 was usually much lower and ranged from 1.95 mg/l in the parr system to 8.6 mg/l in the on-grow system. Because some tanks in each on-grow and 3-year broodstock system were not stocked during this period, the recirculating flow in these systems was restricted by approximately 50% (i.e., only one of the two recycle pumps was operated to conserve energy), which reduced the amount of flow bypassing the fluidized sand biofilters and the flow passing through the CO_2 stripping column by 50%. Because flow was only 50% of the design flow, water did not adequately cover the flow distribution plate at the top of the stripping column and the stripping fan was not operated. When fish loading increases in these systems, recirculating flow will be increased to the design flow and the fans used to ventilate these stripping columns will be turned on, which will improve CO_2 removal in these largest systems.

Alkalinity was lower in systems utilizing freshwater than in systems supplied with brackish water. Alkalinity ranged from a low of 59 mg/l (as calcium carbonate) in parr to a high of 126 mg/lL (as calcium carbonate) in on-grow and broodstock systems. The mean alkalinity was typically near 100 mg/l (as calcium carbonate) and no supplemental sources of alkalinity have been used.

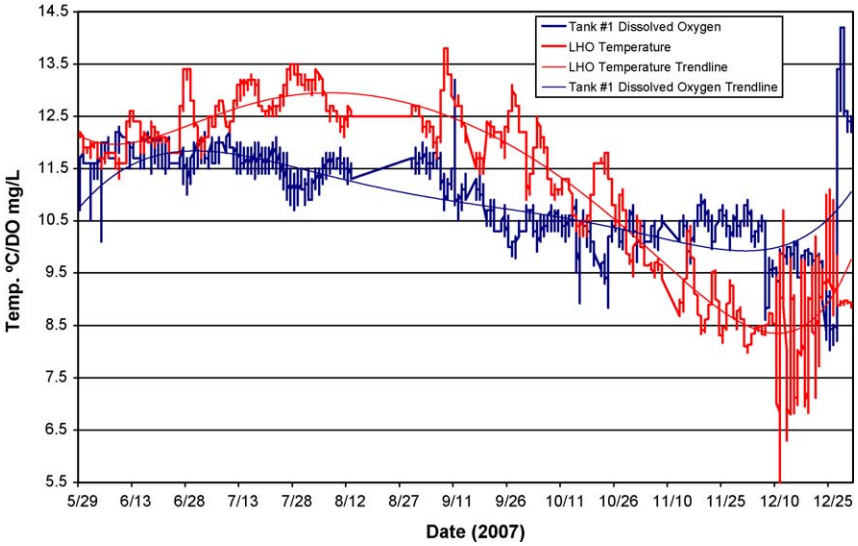


Fig. 10. Variation in water temperature and dissolved oxygen in the on-grow fish culture system at the USDA ARS National Cold Water Marine Aquaculture Center in Franklin, Maine from May through December 2007.

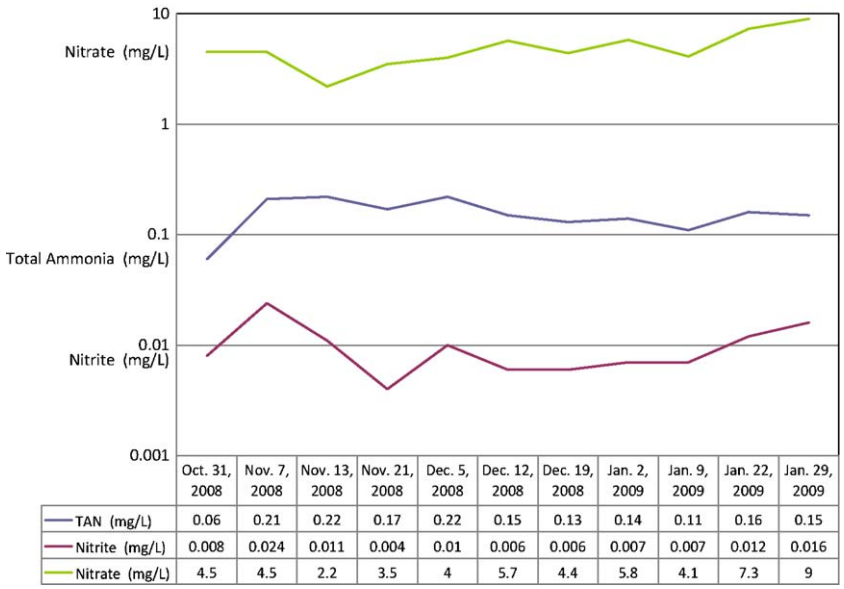


Fig. 11. Changes in total ammonia-, nitrite-, and nitrate-nitrogen in the 3-year broodstock 1 system from October 2008 through January 2009; monthly feed loading was 414, 490, and 512 kg, respectively, in November, December, and January.

Table 6
Water quality parameters measured in the effluent stream related to monthly fish biomass and feed at the USDA ARS National Cold Water Marine Aquaculture Center in Franklin, Maine from June 2007 through December 2007.

Month	Effluent flow rate (l/min)	Max fish bio mass (kg)	Total feed/ month (kg)	Mean BOD (mg/l)	BOD (kg/day)	Mean TSS (mg/l)	TSS (kg/day)	Total nitrogen (mg/l)	Total nitrogen (kg/day)	Mass TSS/ unit feed fed (kg/kg)	Mass BOD/ unit feed fed (kg/kg)	Mass TN/ unit feed fed (kg/kg)	Mean salinity (ppt)
June	435	8,929	1203	2.3	1.43	4.0	2.51	2.13	1.33	0.063	0.036	0.033	NA[a]
July	473	6,071	950	2.3	1.53	8.7	5.93	2.14	1.46	0.194	0.050	0.048	5.40
August	473	7,209	1200	3.0	2.04	4.8	3.27	2.22	1.51	0.084	0.053	0.039	10.90
September	491	9,718	1600	3.8	2.67	5.8	4.07	2.22	1.58	0.076	0.050	0.030	11.60
October	491	10,491	1250	3.0	2.12	4.0	2.83	2.52	1.79	0.070	0.053	0.044	10.70
November	491	14,666	1720	2.2	1.56	13.0	9.21	2.44	1.73	0.161	0.027	0.030	9.00
December	491	1,1007	772	2.5	1.75	5.6	3.97	2.70	1.92	0.159	0.070	0.077	9.10
MEAN	478	9,727	1242	2.73	1.87	6.56	4.54	2.34	1.62	0.115	0.048	0.043	9.45

[a] Salinity was not measured in the effluent stream in June 2007.

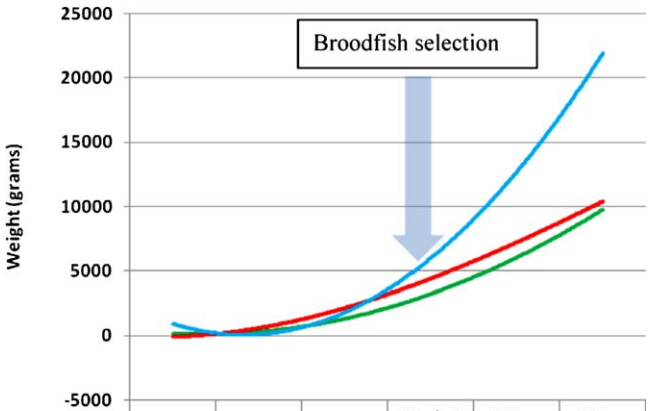
Ozonation maintained excellent water clarity in all recirculating systems and low suspended solids levels, but these were not quantified.

3.2. Effluent treatment system performance

Total suspended solids (TSS), total nitrogen (TN), and biological oxygen (BOD) demand in the effluent were somewhat but not strictly related to biomass and feeding rates (Table 6). Total nitrogen (kg/day) discharged through in the effluent ranged from 1.33 kg/day in June 2007 to 1.92 kg/day in December 2007 with a mean of 1.62 kg/day. The drum filters, biological filters, radial flow clarifiers, and solids concentration filtration in the effluent building were effective in reducing BOD, TSS, and TN in the effluent discharge. The mean TSS concentration in the effluent ranged from 2.51 kg/day in June 2007 to 9.21 kg/day in November 2007. The drum filters, radial flow clarifiers and effluent building equipment removed (as waste biosolids) all but 11.5% of the monthly mass of feed fed (Table 6). BOD in the effluent ranged from 1.43 kg/day in June 2007 to 2.67 kg/day in September 2007, which was 4.8% of the mean monthly feed mass. If nitrogen composes approximately 7% of the feed, then approximately 61% of the nitrogen added through the feed on a mean monthly basis was discharged in the effluent (Table 6).

3.3. Fish performance

In the spring of 2007, the parr, on-grow, and 3-year broodstock systems were stocked using fish that had been cultured in temporary facilities since December 2003. Fish growth was acceptable in the different systems from June 2007 through January 2008 (Fig. 12). Parr grew from 0.1 to 40 g, 2-year-old salmon from 185 to 1310 g, and 3-year-old salmon from 816 to 2170, and 4-year-old salmon from 2600 to 6947. Salmon cultured at the NCWMAC research facility were smaller, but similar sized to salmon cultured at a commercial land-based facility (Fig. 12). Because the NCWMAC is a research facility with a focus on an Atlantic salmon breeding program, fish size is not of critical importance. High densities maintained in previous temporary rearing conditions and low temperatures during the winter months impacted fish sizes during this time period. Feeding rates were below predicted maximum feeding rates, but are likely to approach design levels in the future as fish numbers and biomass increase. The maximum amount of feed per day has been 57.4 kg; however, design specifications allow that up to 467 kg/day could be provided if fish culture systems were stocked at maximum biomass. Computer controlled automatic feeding systems have been efficient at providing feed and maintain accurate records of fish numbers, biomass, and quantities of feed used in the facility (Fig. 12).



	Parr	Smolt	2 Year	Market Size	4 Year Brood	5 Year Brood
NCWMAC	45	120	2179		4941	10353
Commerical	50	140	2600		7000	10500
Seawater		110	1800	6000		

Fig. 12. Typical weight (g) for Atlantic salmon cultured at the USDA ARS National Cold Water Marine Aquaculture Center (NCWMAC) in Franklin, Maine (green line), similar data obtained from a commercial Atlantic salmon hatchery in Maine (red line), and a net pen site in Maine (blue line) (Personal communication from David Miller and Greg Lambert, Cooke Aquaculture, U.S.). Selection of superior broodfish typically occurs in year 3 of breeding program (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.).

4. Conclusions

Atlantic salmon cultured in the NCWMAC breeding program grew well during the first 7–8 months of operation in the reuse fish culture systems. The systems were operated at approximately 98% reuse (2% makeup water on the basis of flow rate). Water quality in the fish culture systems was acceptable for Atlantic salmon culture and was nearly the same as flow through culture systems.

Several advantages for utilizing reuse fish culture systems were evident for culturing Atlantic salmon. The Franklin location has limited ground water so reuse systems are the only possible technology for culturing the relatively large salmon biomass required for the research program. The design of the effluent system and characteristics wastewater flow from the facility demonstrates better solids capture than flow through fish culture systems. The use of groundwater, reuse culture technologies, and effective biosecurity protocols has resulted in fish health certification for the facility and fish stocks. No mortality events or pathogens of regulatory concern have been reported on any fish health checks. All fish stocks were screened biannually for five viruses (IPNV, IHNV, ISAV, OMV, VHSV), along with Aeromonas salmonicida, Yersinia ruckeri, Renibacterium salmoninarum, Myxobolus cerebralis, and Ceratomyxa shasta. Water temperature in the fish culture systems has been largely maintained by passive heating or cooling of makeup water flowing through the well water tower. No expensive supplemental heating or cooling has been required.

The research objective focusing on the development of an Atlantic salmon breeding program has been successful. The first generation of salmon obtained in 2003 was performance evaluated in industry net pens, captive broodfish were maintained at the Franklin site in reuse systems, and the broodfish were spawned in the fall of 2007. Approximately 500,000 unfertilized eggs from selected broodfish were transferred to commercial producers and consumers through a cooperative agreement with industry.

Acknowledgments

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